SAND2020-1932C

Magnetic sensing using nitrogen-vacancy centers in diamond

Pauli Kehayias

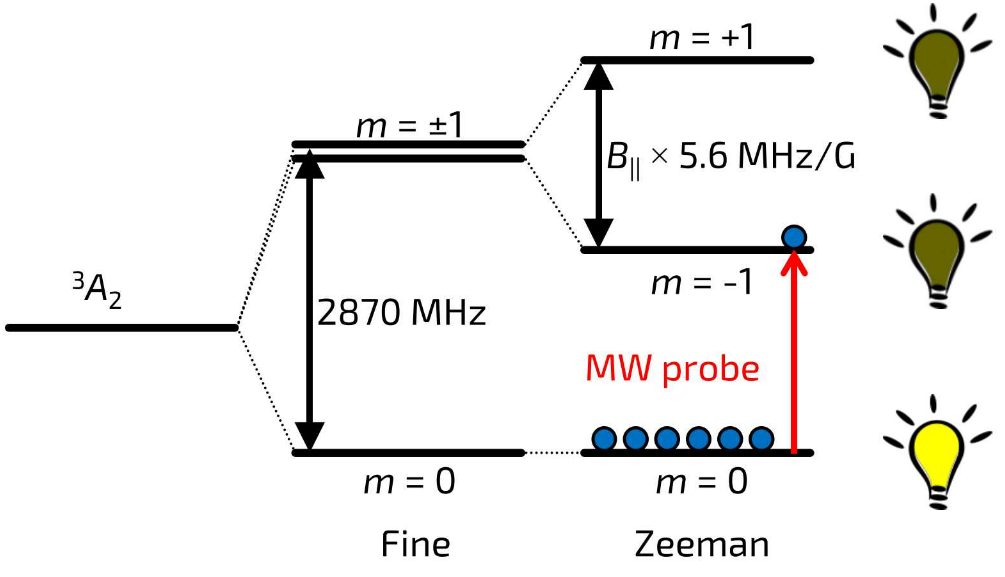
Sandia National Laboratories

February 22, 2020

SAND2020-XXXXX

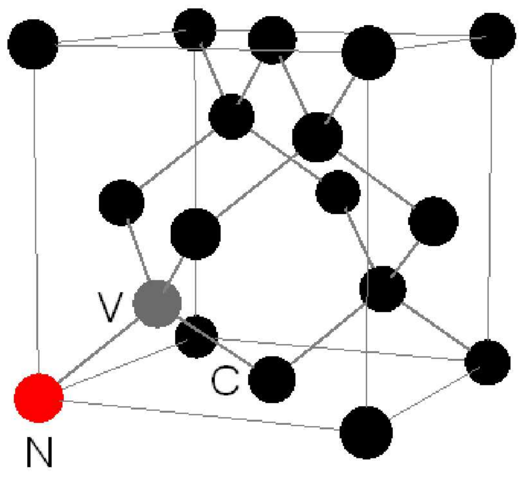
The author gratefully acknowledges support from the Sandia National Laboratories Truman Fellowship Program, which is funded by the Laboratory Directed Research and Development (LDRD) Program at Sandia National Laboratories, a multi-mission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

NV diamond overview

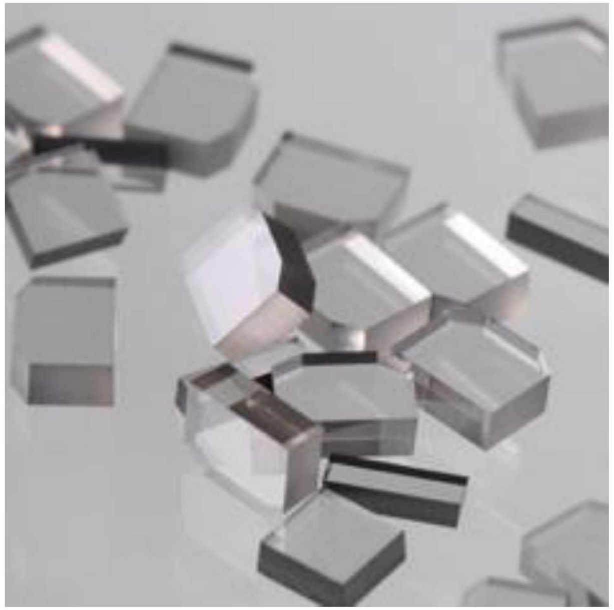


Naturally-occurring paramagnetic color centers

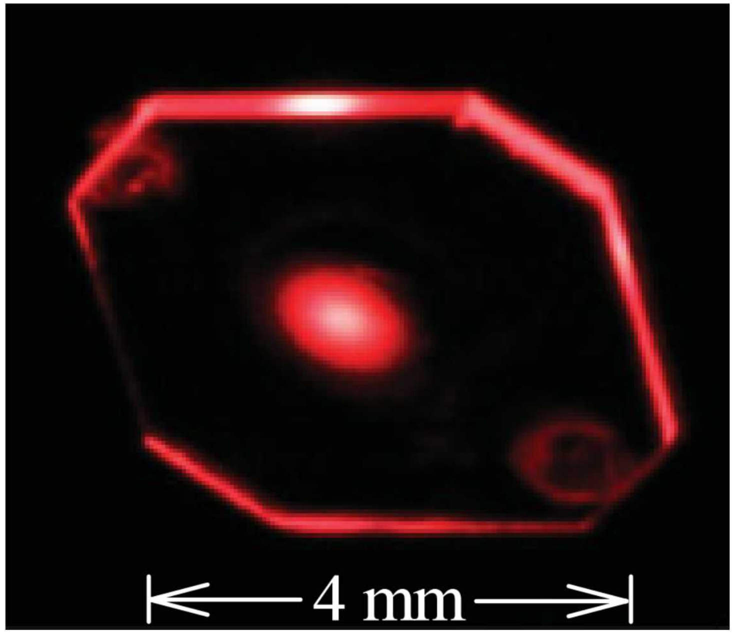
Discrete electronic states
- Magnetically-sensitive ground state
- Optical initialization & readout
- Sublevel-dependent fluorescence
- DC to GHz magnetometry



Synthetic diamond chips (few mm)



NV fluorescence under illumination



D. Le Sage et al., PRB 85 121202(R) (2012)
R. Schirhagl et al., Ann. Rev. Phys. Chem. 65 83-105 (2014)

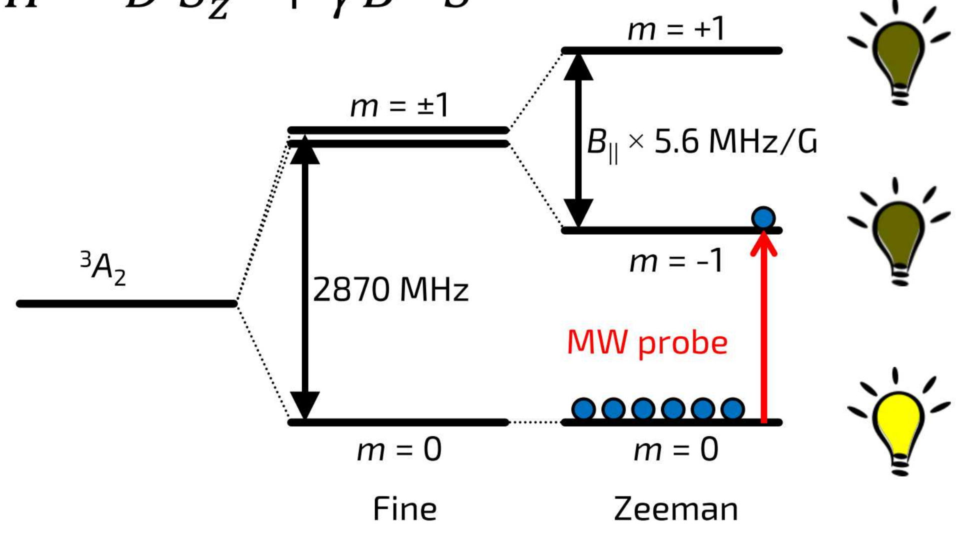
Optically detected magnetic resonance (ODMR)

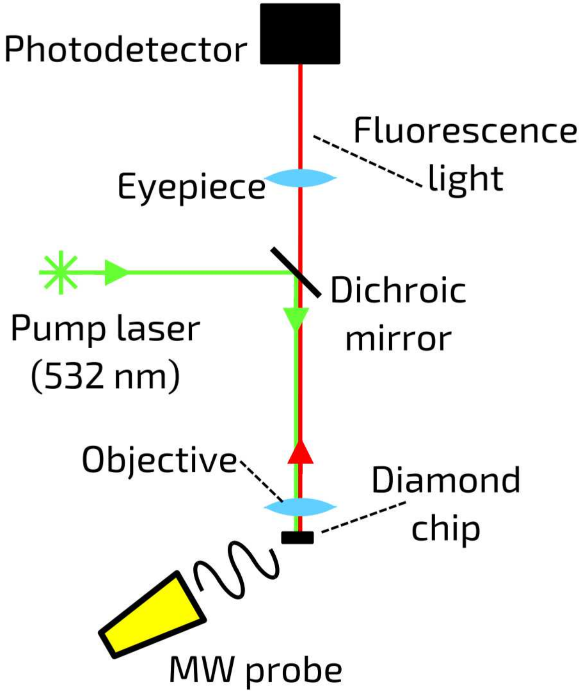
Optically pump NVs to m = 0 bright state

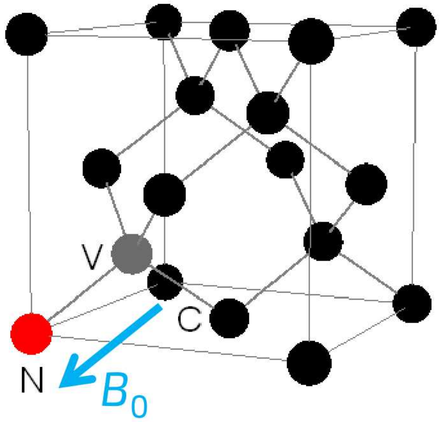
Resonant MW drive transitions to m = ±1, spoil optical pumping

Use resonance frequencies to extract B

$$H = D\,S_z{}^2 + \gamma \vec{B} \cdot \vec{S}$$





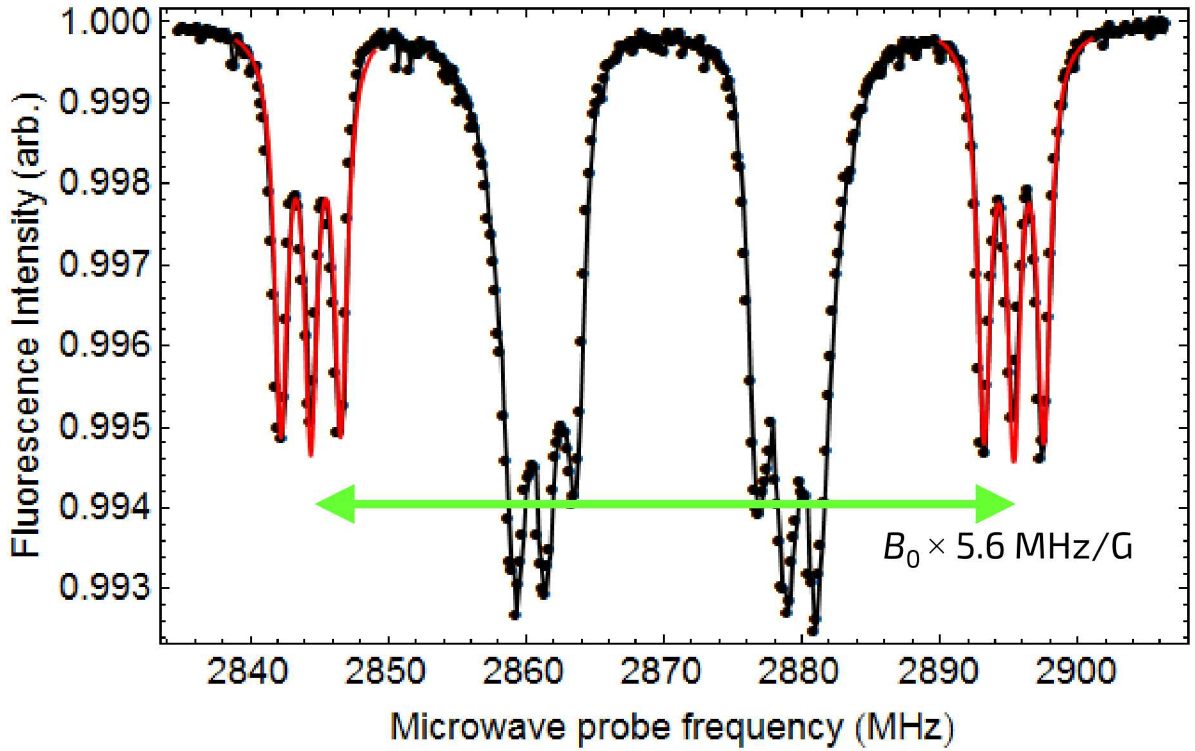


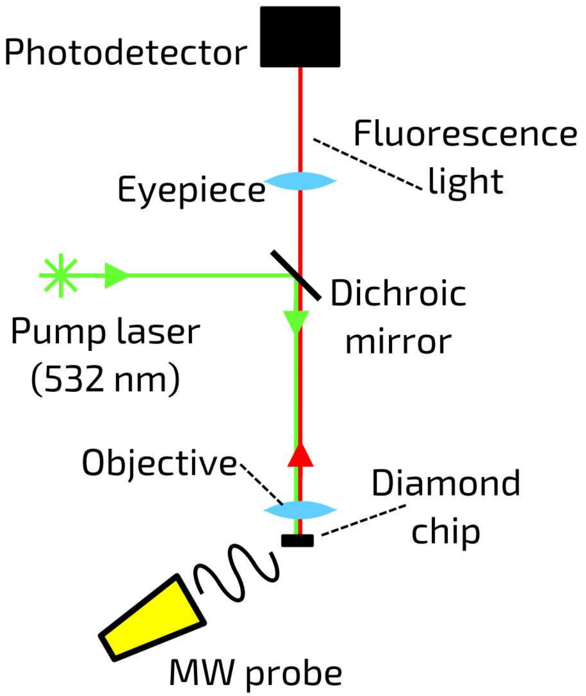
Optically detected magnetic resonance (ODMR)

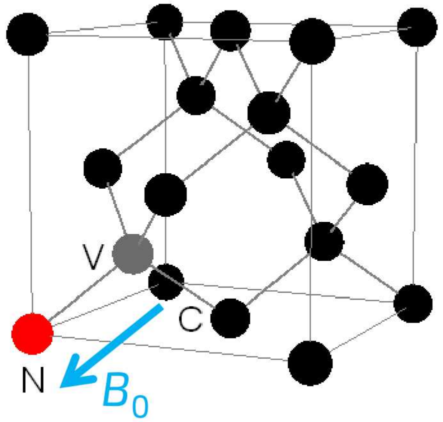
Optically pump NVs to m = 0 bright state

Resonant MW drive transitions to m = ±1, spoil optical pumping

Use resonance frequencies to extract B



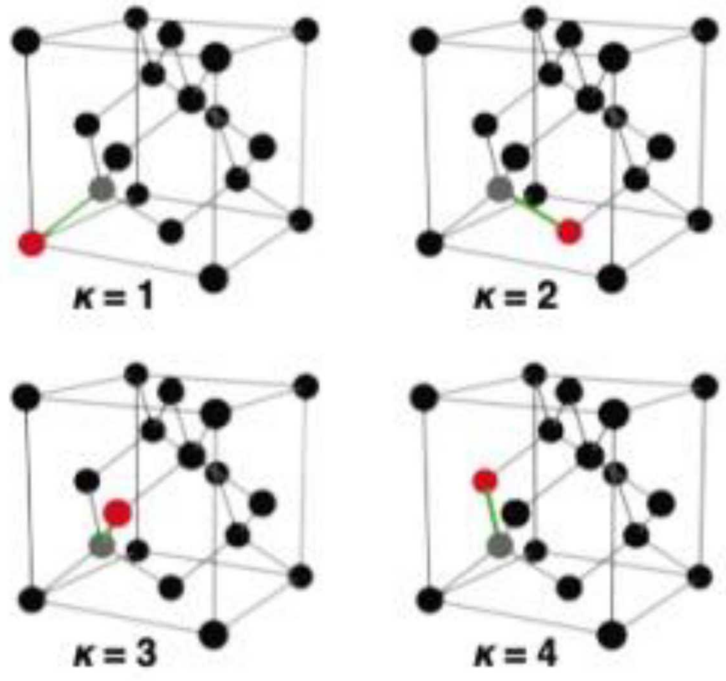




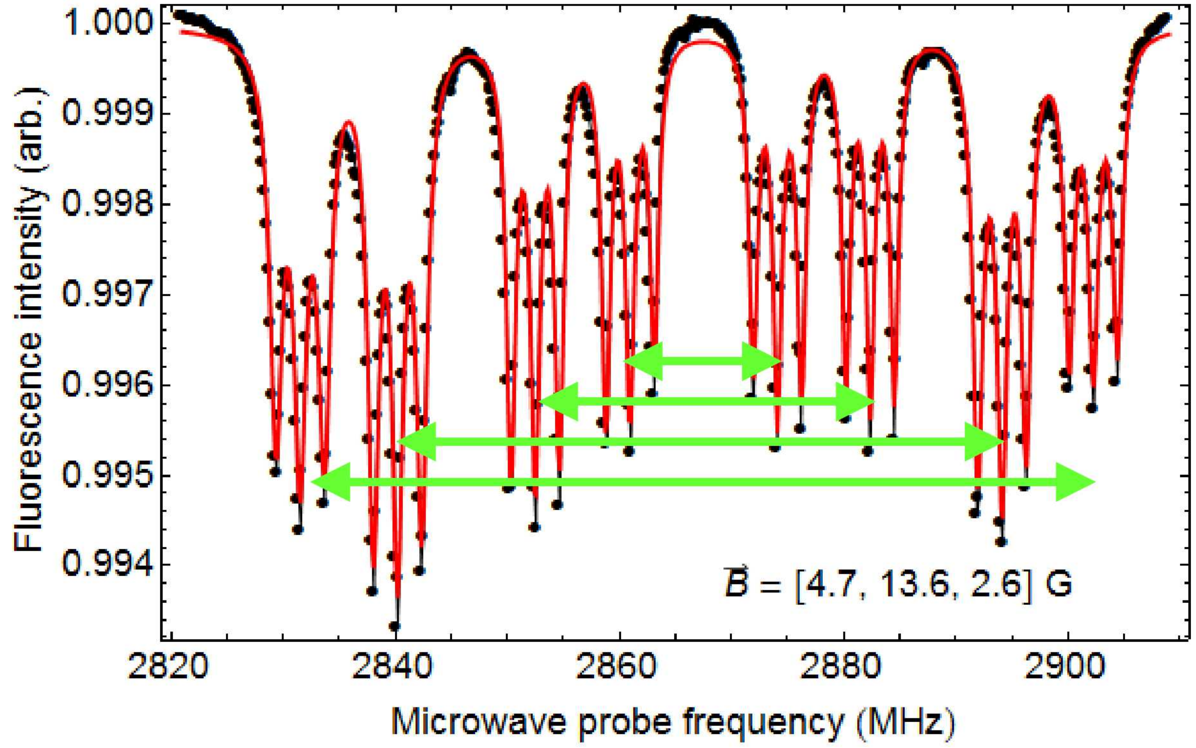
Vector magnetometry

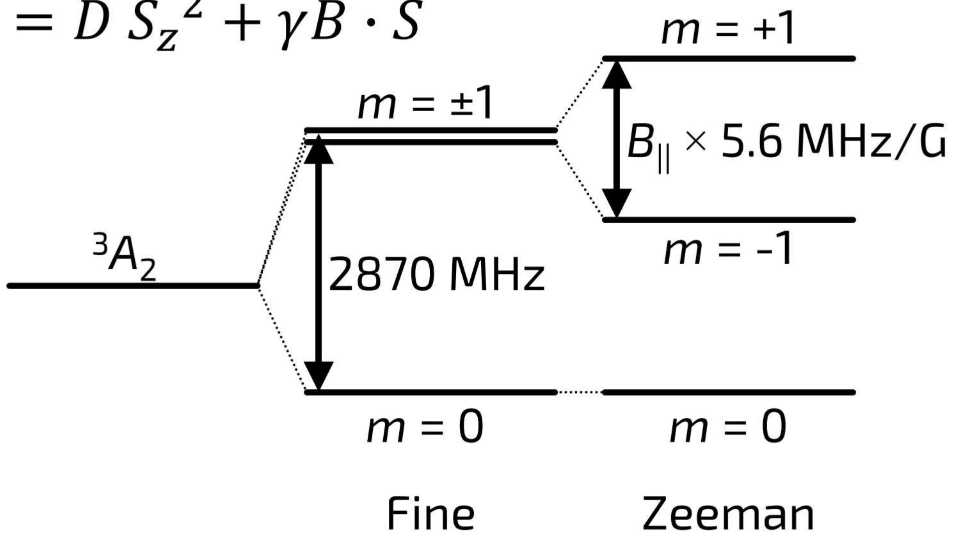
Bias field splits resonances for each NV orientation

Reconstruct $\{B_x, B_y, B_z\}$ from the NV Hamiltonian



$$H = D\, S_z{}^2 + \gamma \vec{B} \cdot \vec{S}$$





Why use NV magnetometry?

Optical control & readout

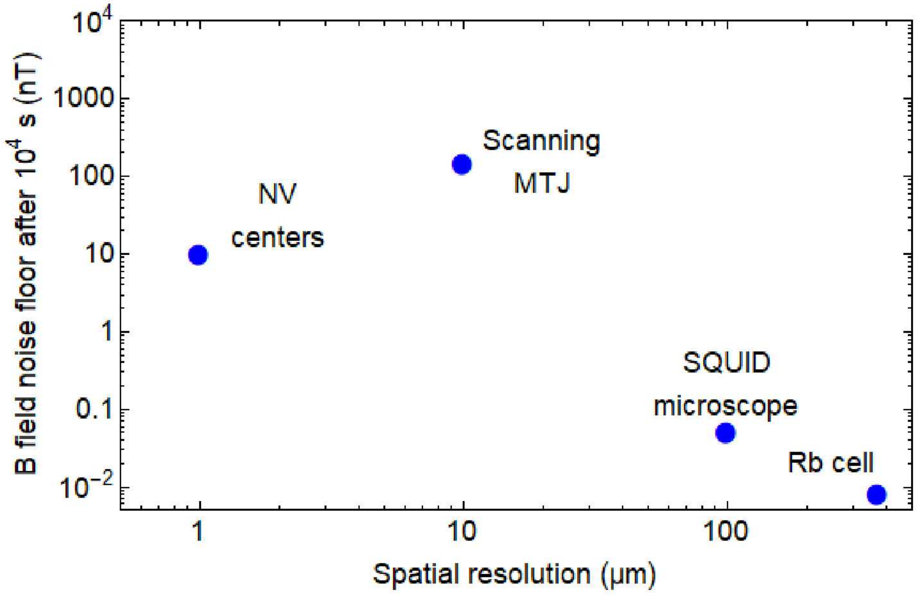
Few-ms lifetime at room temperature

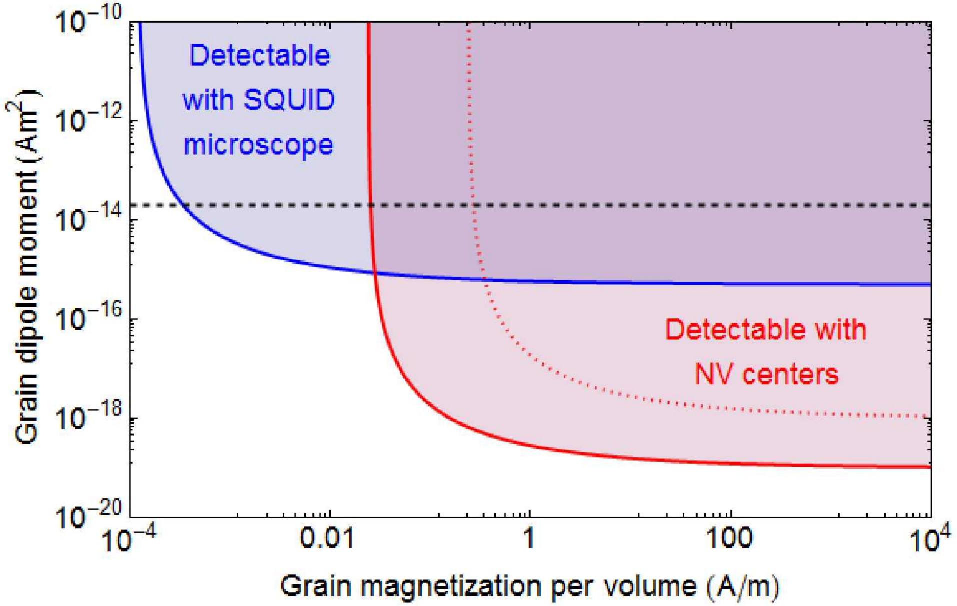
Works in ambient conditions, biocompatible

Small sensor-target separation

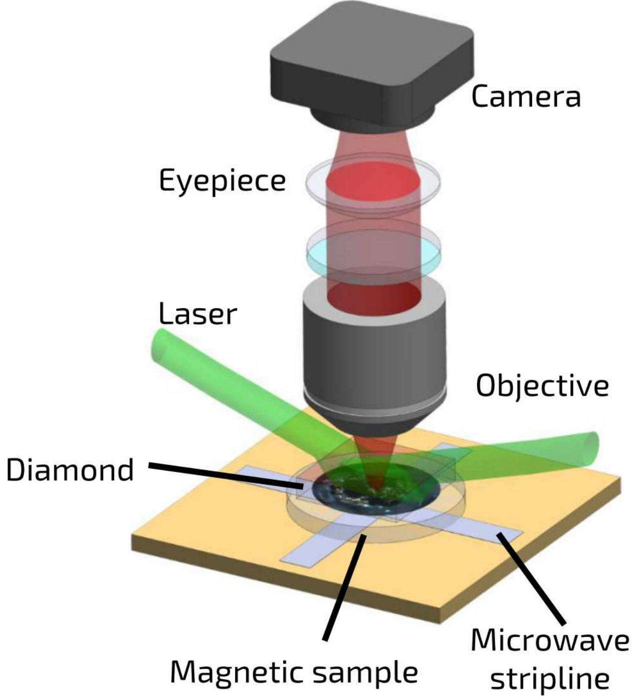
Ideal for sensing small samples

Magnetic sensitivity vs. spatial resolution





NVs are good for high-res magnetic imaging

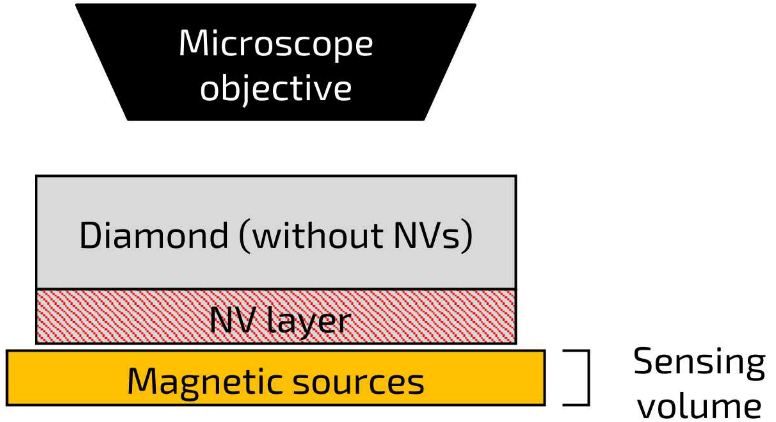


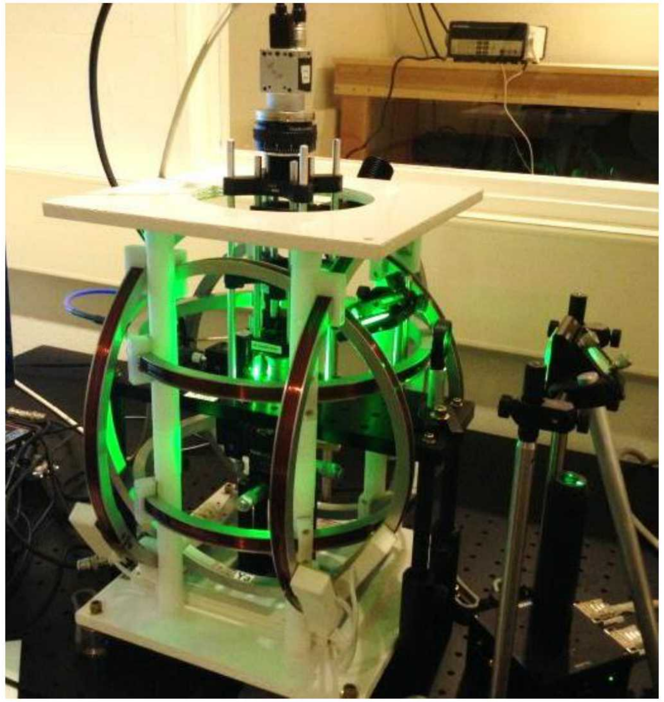
NV imager details:

- Few-mm FOV, micron spatial resolution
- Overlay optical and magnetic images
- Sensitive to deep sources (rather than surface magnetization)
- Parallel acquisition (no sensor scanning)
- No cryogens or vacuum

Contributions to magnetic spatial resolution:

- Standoff distance
- NV layer thickness
- Optical diffraction limit

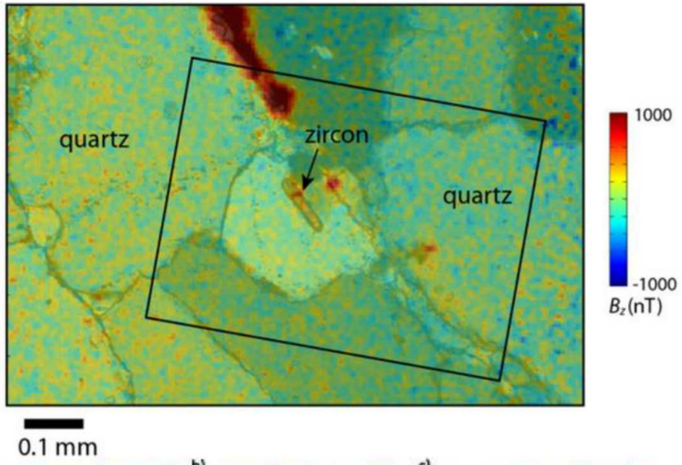


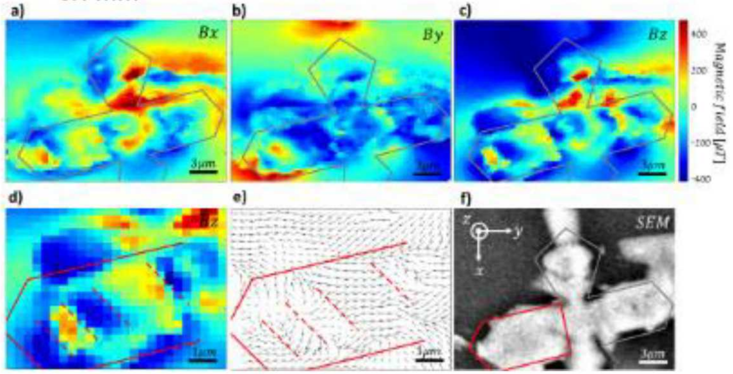


D. R. Glenn et al., Geochem Geophys Geosyst 18, 8 (2017)
E. V. Levine et al., Nanophotonics 8 11 1945-1973 (2019)

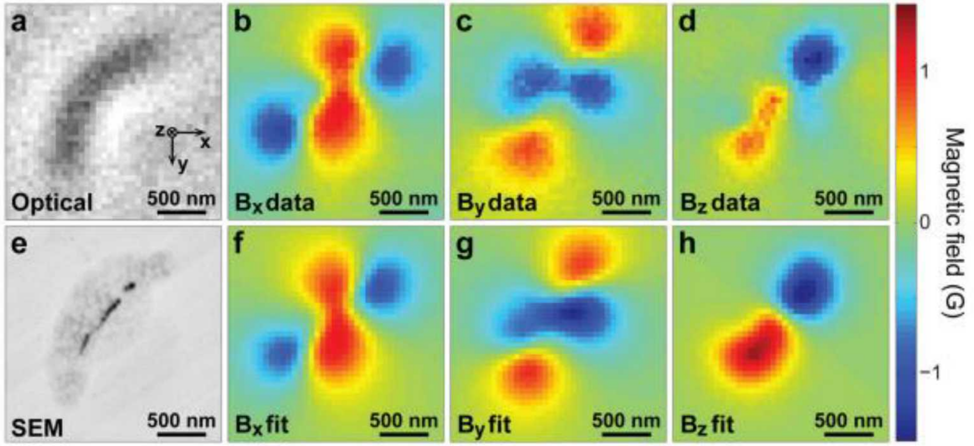
NV magnetic imaging highlights

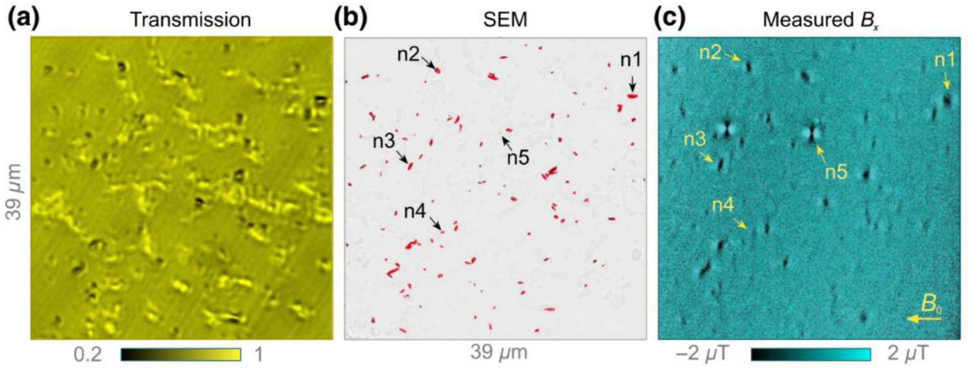
Geomagnetism



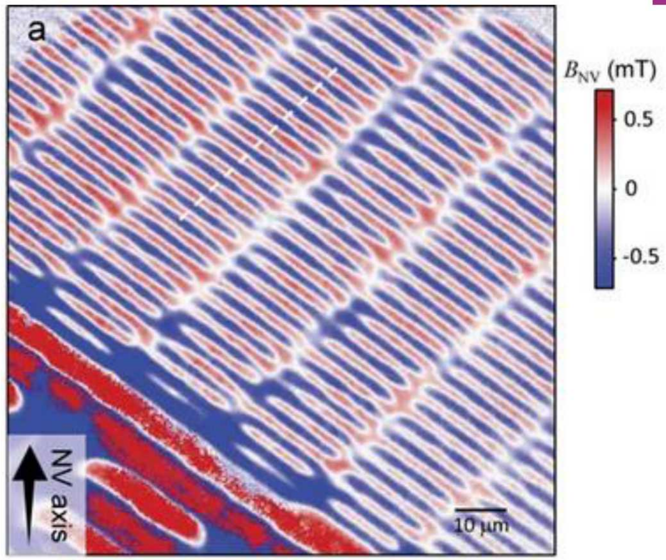


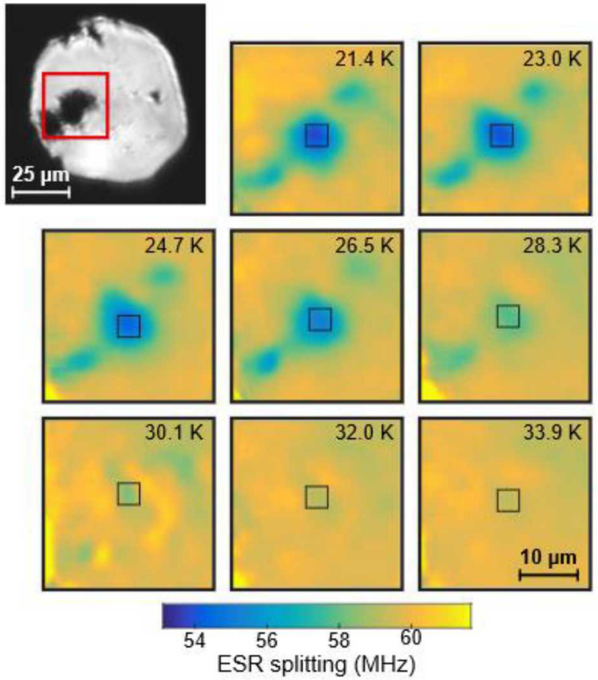
Biomagnetism





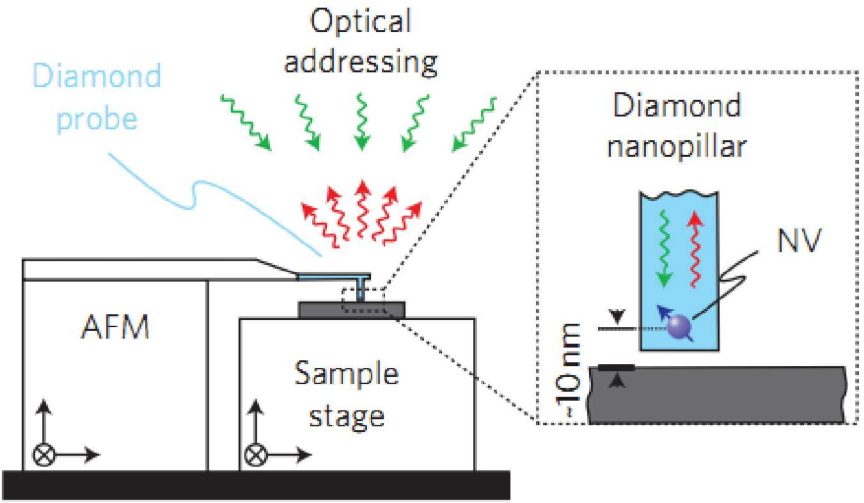
Condensed-matter physics



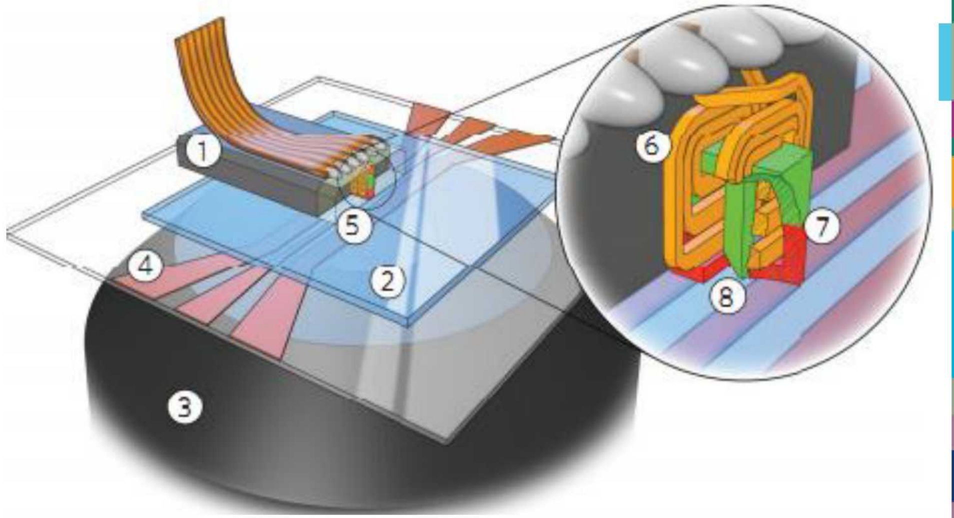


B. P. Weiss et al., Geology 46 5, 427-430 (2018)
E. Farchi et al., Spin 07 03 1740015 (2017)
D. Le Sage et al., Nature 496, 486-489 (2013)
I. Fescenko et al., Phys. Rev. Applied 11 034029 (2019)
D. A. Simpson et al., Sci. Rep. 6 22797 (2016)
M. Lesik et al., Science 366 6471 (2019)

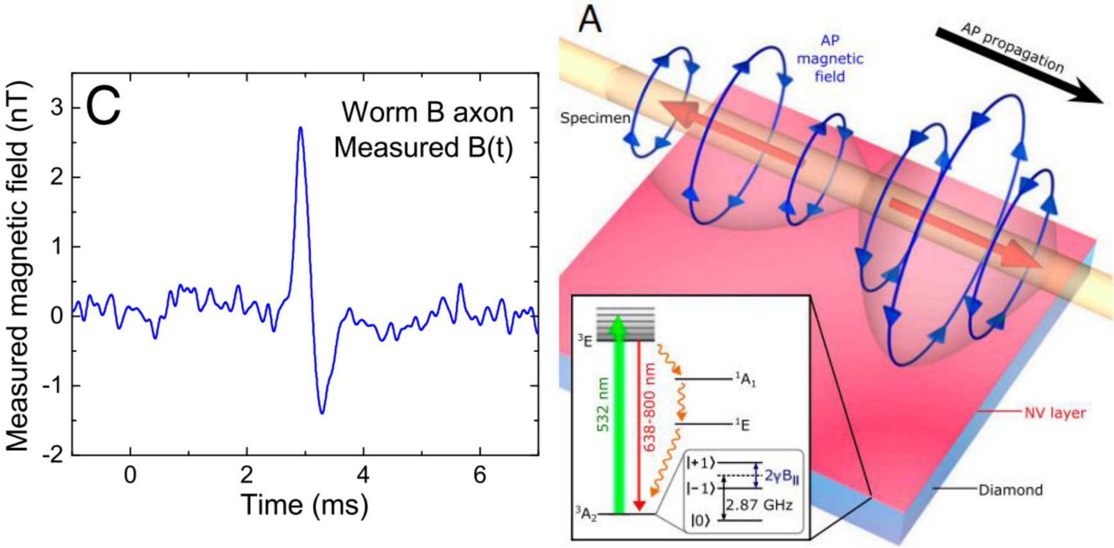
NV single-pixel magnetometry highlights



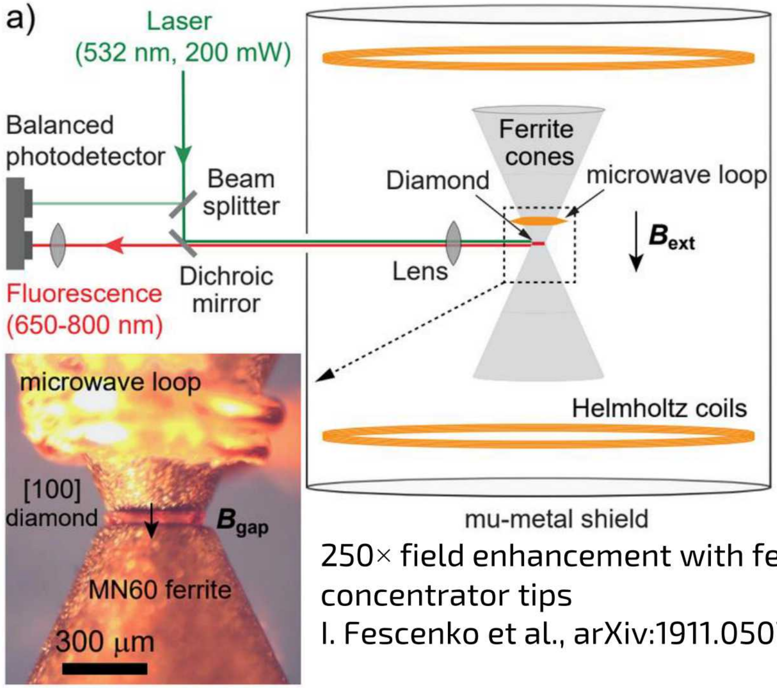
Scanning NV on a cantilever
P. Maletinsky et al., Nature Nano. 7 320 (2012)



NV hard-drive read-write head magnetometer
I. Jakobi et al., Nature Nano. 12, 67-72 (2017)



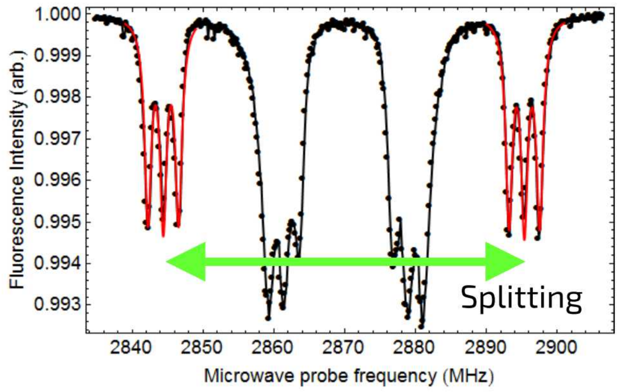
Magnetic field from a marine worm neuron
J. F. Barry et al., PNAS 496 113 14133-14138 (2016)

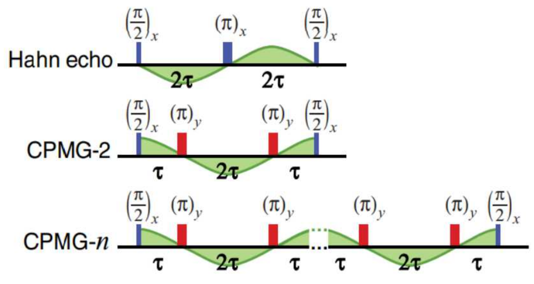


250× field enhancement with ferrite flux concentrator tips
I. Fescenko et al., arXiv:1911.05070 (2019)

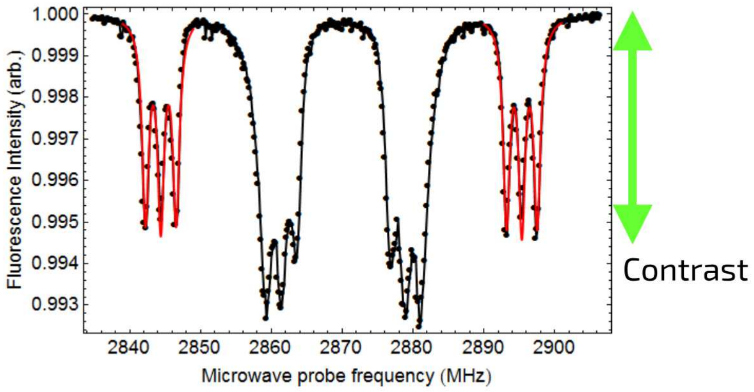
NV magnetometry technique summary

	DC to 10 kHz	10 kHz to 10 MHz	10 MHz to 100 GHz
Techniques	- CW ODMR - Pulsed ODMR - Ramsey interferometry	- Dynamical decoupling - Correlation spectroscopy - Spin locking	- CW ODMR - Rabi driving - Double electron-electron resonance (DEER) - NV T_1 relaxation
Applications	- Paleomag & rock mag - Biomag - Navigation - 2D magnetic structures - Low-frequency electronics	- Small-volume NMR - 2D magnetic structures - RF electronics	- Electron paramagnetic resonance (EPR) - 2D magnetic structures - MW electronics

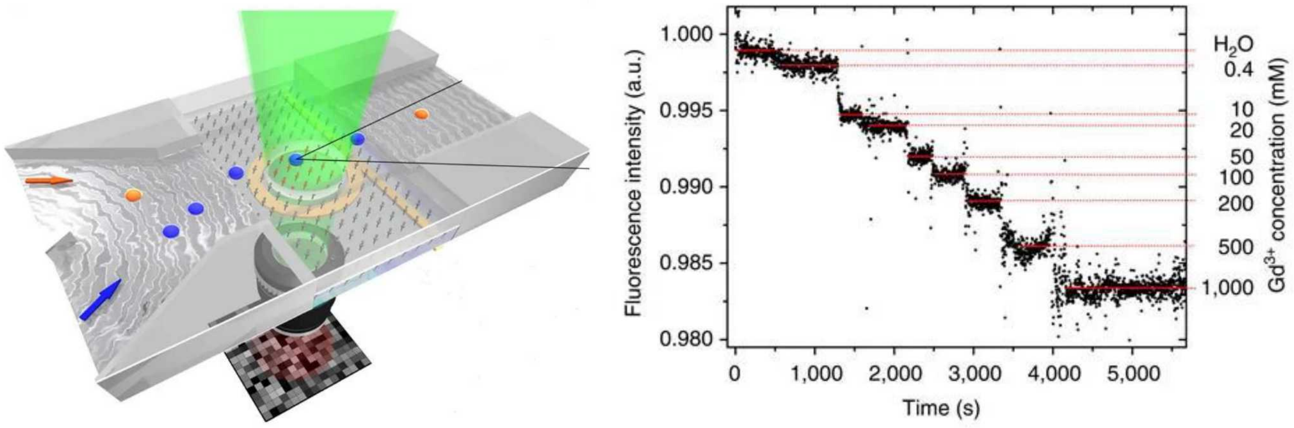




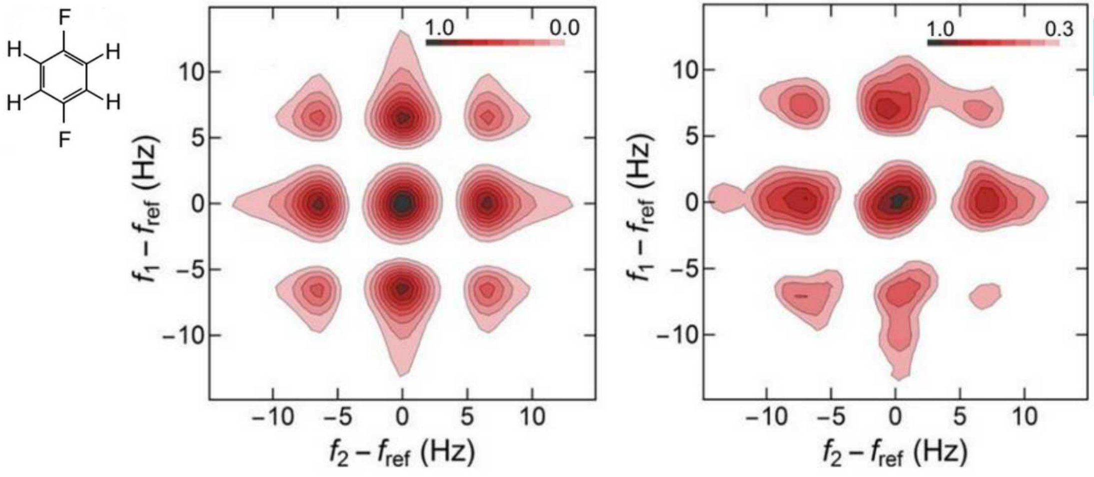
Dynamical decoupling



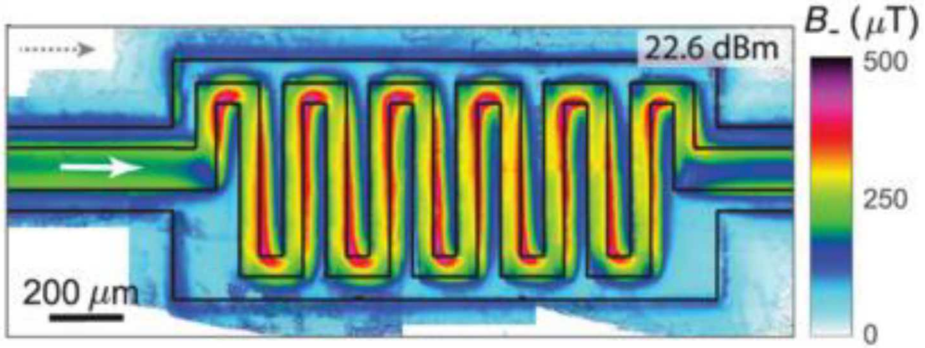
NV AC magnetometry highlights



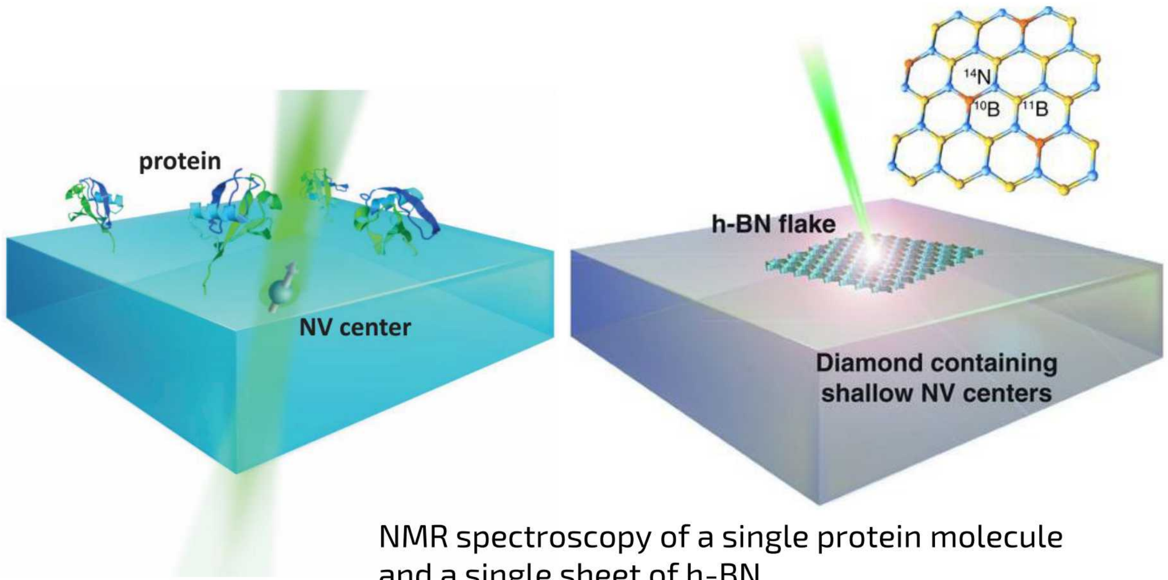
NV T_1 relaxation from Gd^{3+} magnetic noise
S. Steinert et al., Nat Comm 4 1607 (2013)



2D correlation spectroscopy of 40 pL 1,4-difluorobenzene
J. Smits et al., Sci Adv 5 eaaw7895 (2019)



NV microwave imaging of a meandering waveguide
A. Horsley et al., Phys Rev Applied 10 044039 (2018)

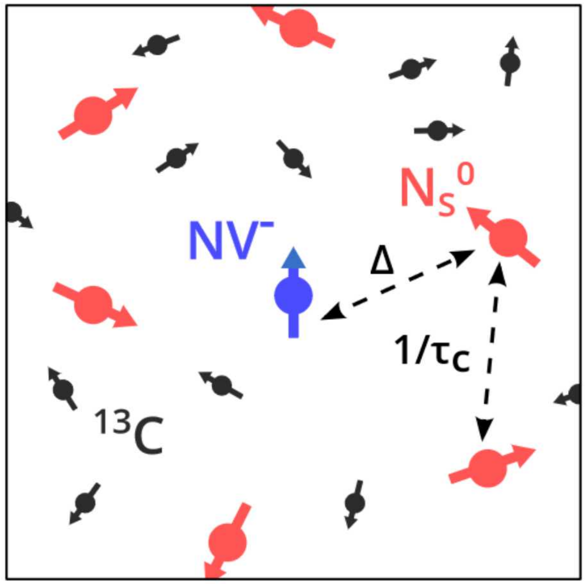


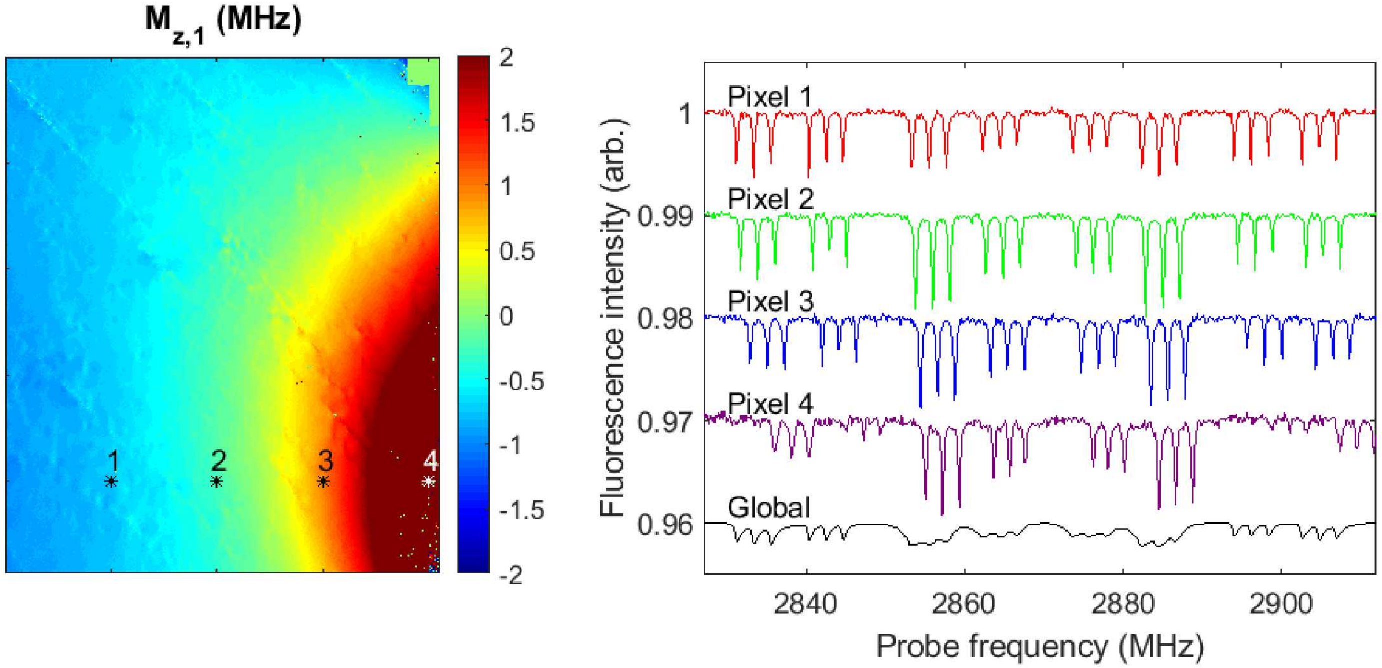
NMR spectroscopy of a single protein molecule
and a single sheet of h-BN
I. Lovchinsky et al., Science 351 6376 (2016)
I. Lovchinsky et al., Science 355 6324 (2017)

Current limitations

T_2* linewidth broadening
- Magnetic defects (^{13}C, paramagnetic nitrogen, …)
- Strain & electric field inhomogeneity
- Diamond sample fabrication challenges

Uniform NV local environments leads to better sensitivity



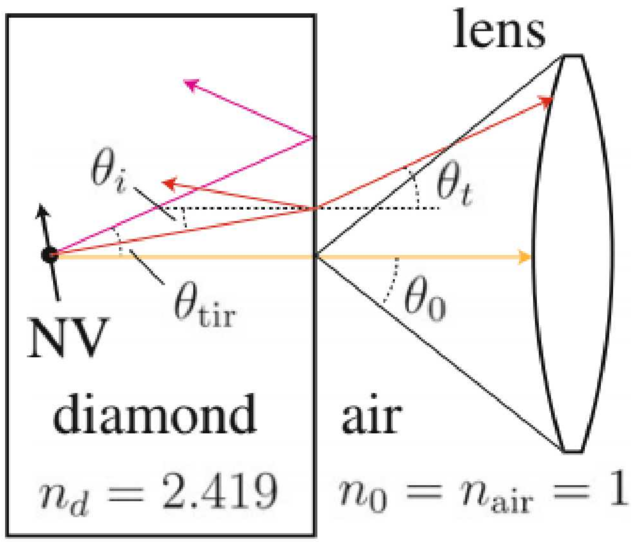


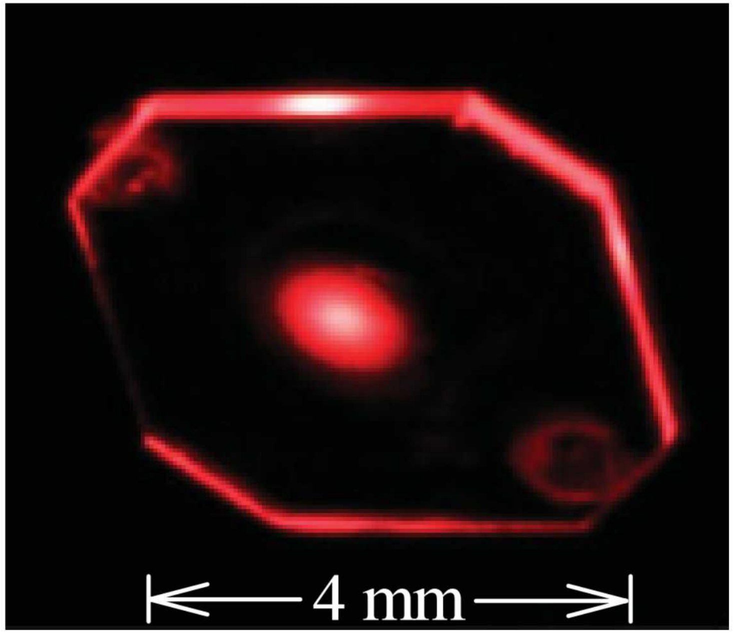
E. Bauch et al., arXiv:1904.08763 (2019)
P. Kehayias et al., PRB 100, 174103 (2019)

Current limitations

Optical readout
- Poor collection efficiency
- Few-percent contrast
- Photon shot noise limit instead of spin projection noise limit
- Photon noise only improves like $\sqrt{N_\gamma}$

Improved photon noise or non-fluorescence readout can lead to better sensitivity



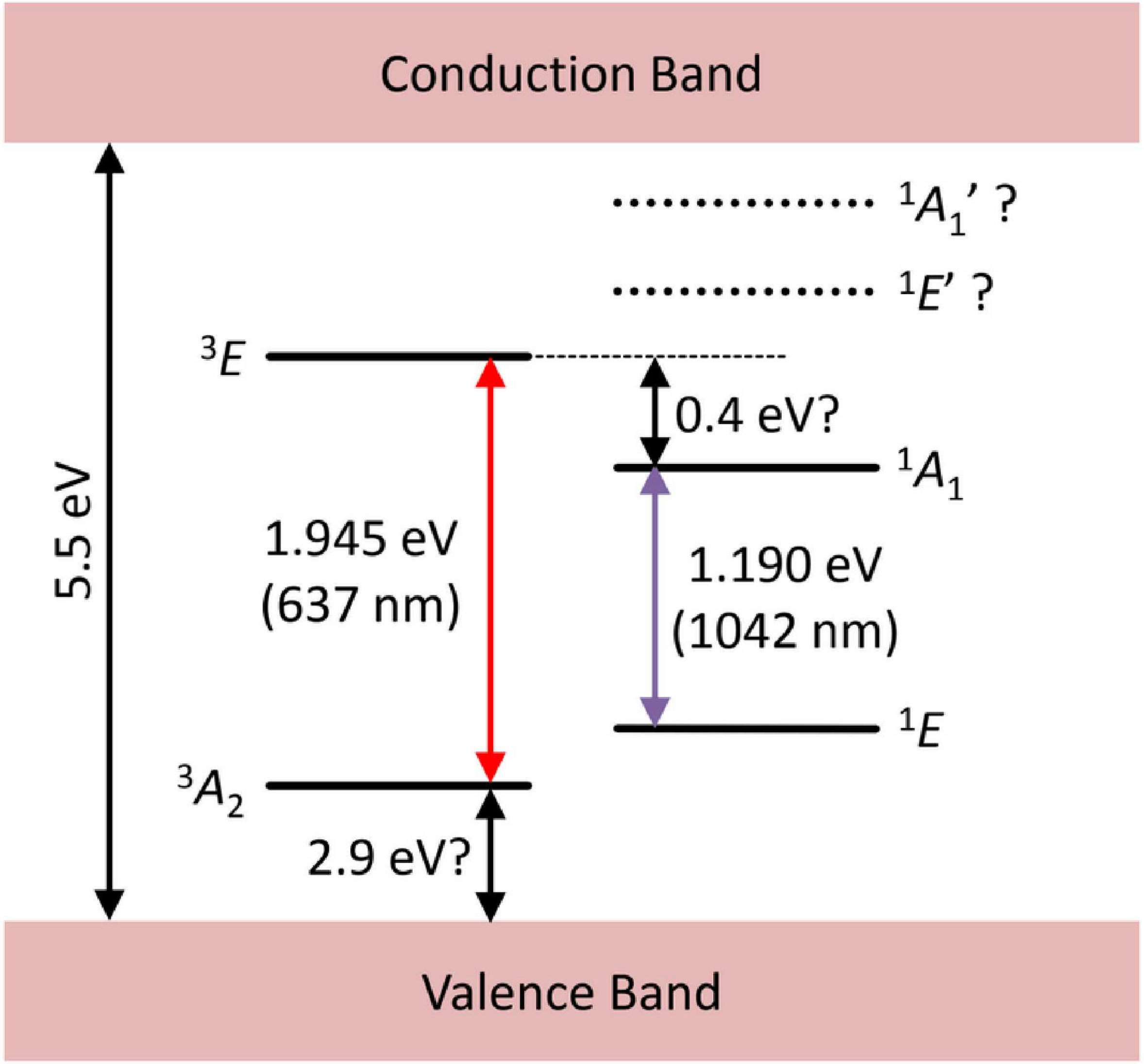


K. Jensen et al., High Sensitivity Magnetometers pp. 553-576 (2017)
D. Le Sage et al., PRB 85 121202(R) (2012)

Current limitations

Gaps in basic properties knowledge
- Unobserved singlet states
- Single-triplet energy separation
- Optical pumping mechanism
- Photoionization dynamics & charge-state ratio

A more complete understanding can inform more optimized sensing & readout techniques



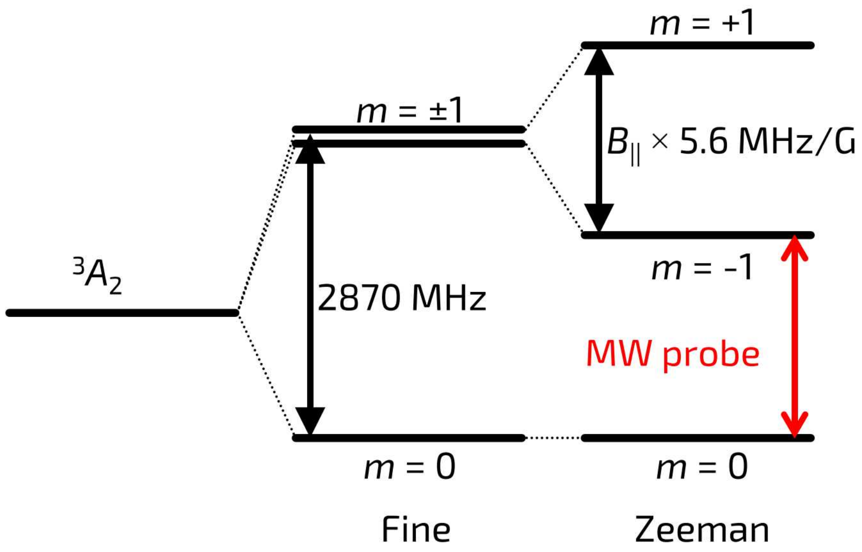
M. L. Goldman et al., PRL 114 145502 (2015)
N. Aslam et al., NJP 15 013064 (2013)

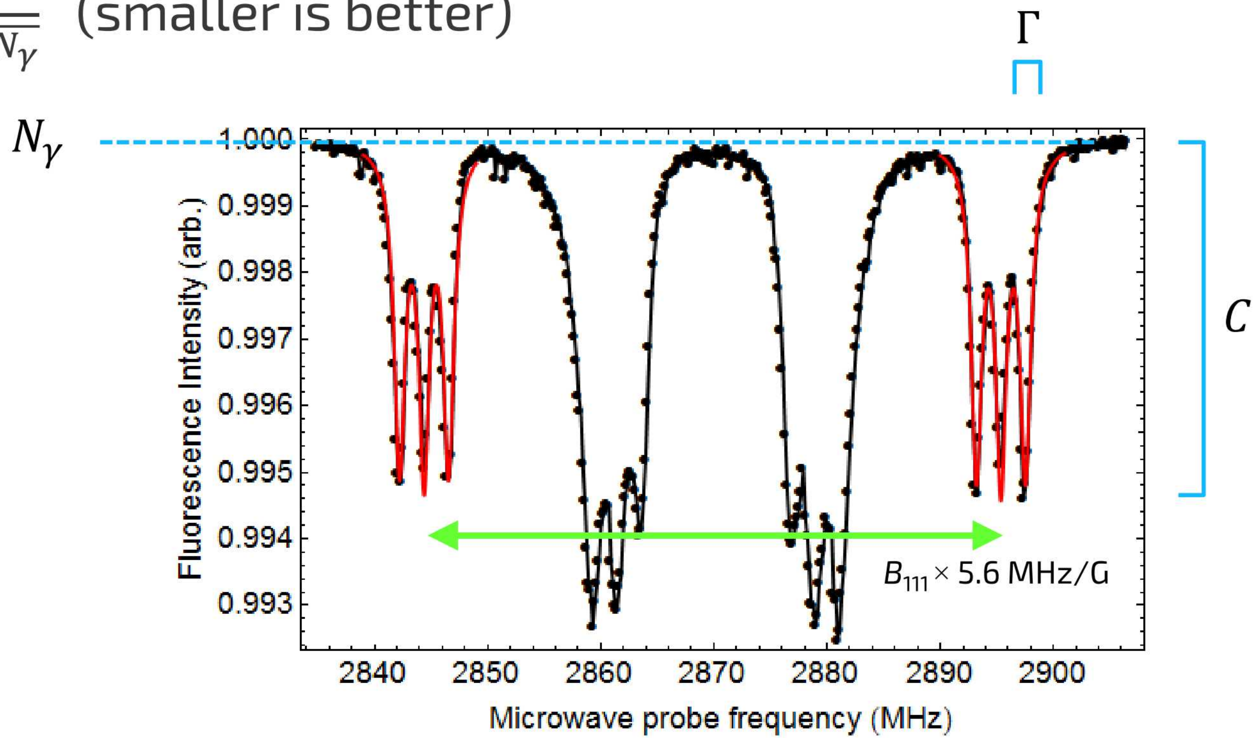
Outlook

NV sensitivity improvements will enable new applications

- Biomagnetism
- Magnetic navigation
- Rotation sensing
- Diamond anvil cell sensing

NV photon shot noise magnetic noise floor: $\Delta B \sim \frac{\Gamma}{C\sqrt{N_\gamma}}$ (smaller is better)





Outlook

Room for improvement
- Linewidth & contrast boosts are the most promising
- Current sensitivity still far from the spin projection noise

Dual approach for improved sensitivity:
- Improved diamond samples
- Optimized NV readout techniques

Investigate other optically-active defects
- In diamond: SiV, SnV, PbV, ST1, …
- In other solids (SiC polymorphs, …)

Ideas for new NV sensing applications
- Magnetic imaging with small standoff
- Temperature, pressure, and electric field sensing
- Extreme environments

Magnetic sensitivity vs. spatial resolution